I-07

Advanced Tokamak Research in JT-60U and JT-60SA

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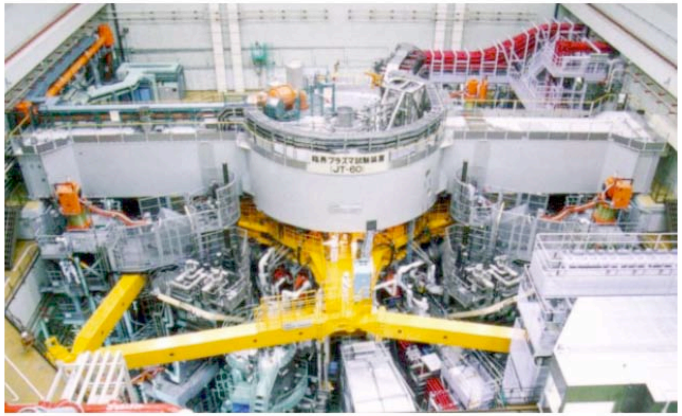
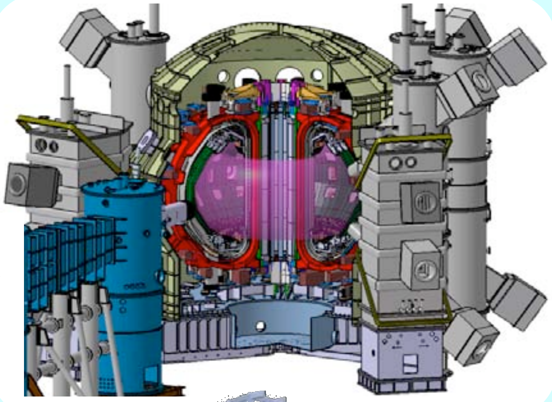
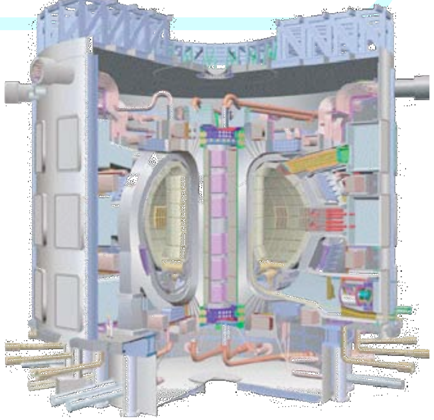
JT-60U

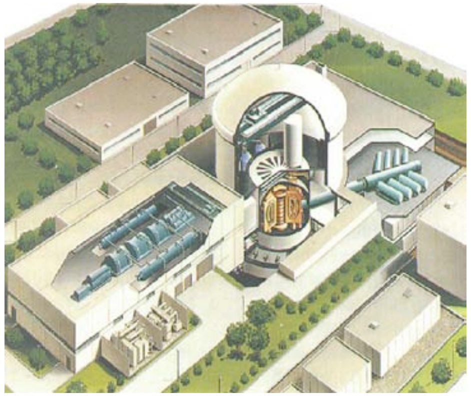


JT-60SA



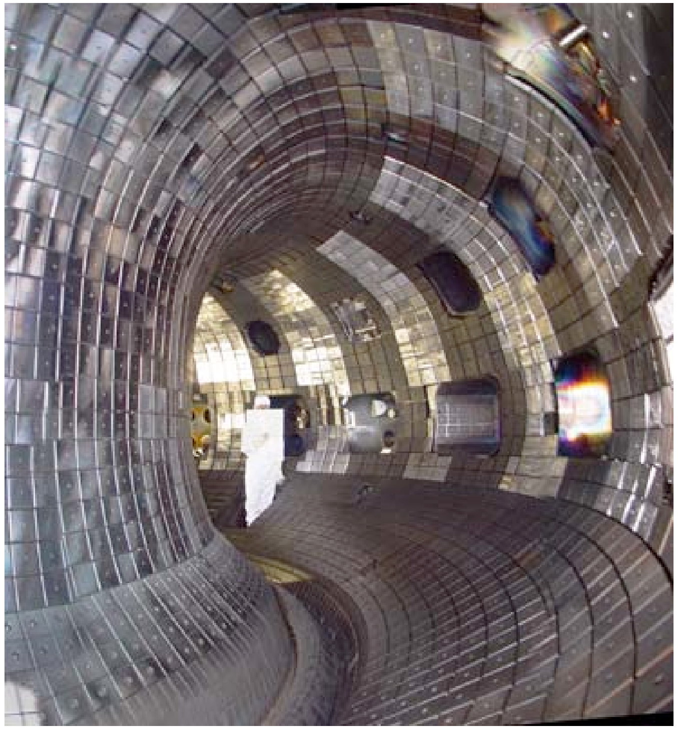


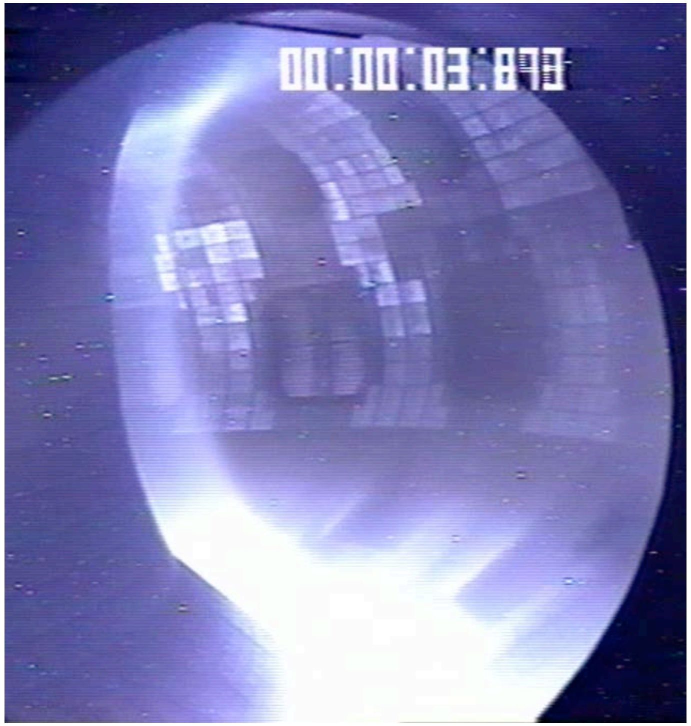
ITER



DEMO

Advanced tokamak development in JT-60U





Advanced Tokamak research in JT-60U

JT-60U

- In ITER & DEMO, simultaneous achievement of
  - High beta (β_N)
  - High confinement ($H_{H98(y,2)}$)
  - High non-inductive CD fraction f_{NI} (=f_{BS}+f_{CD})

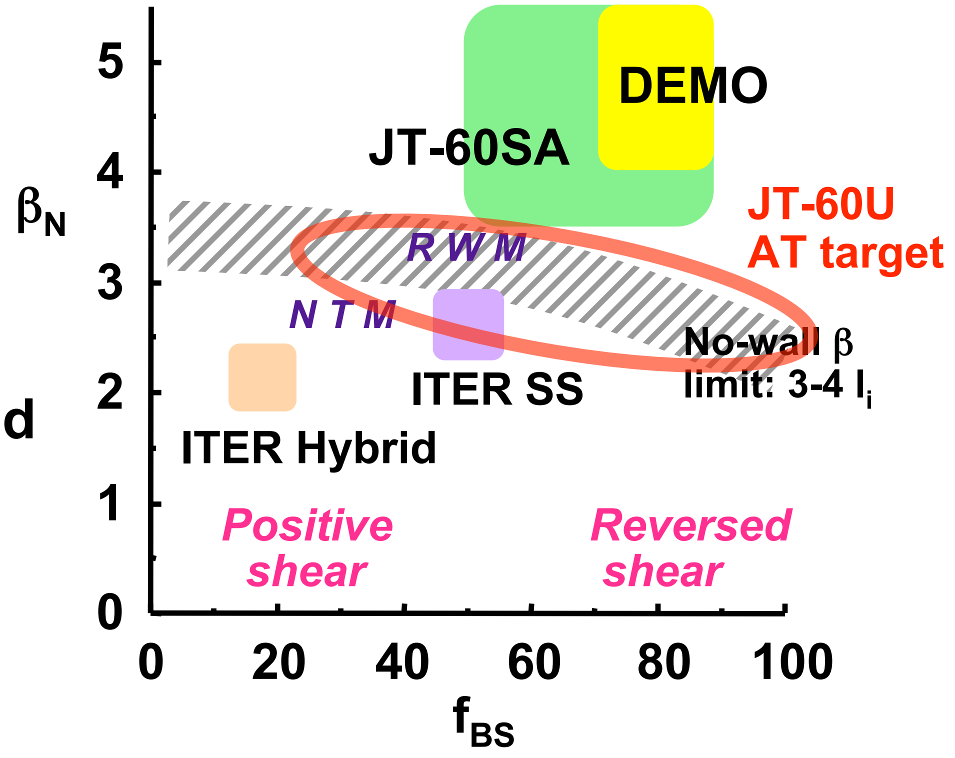
  with sufficient duration is required

This talk

- In JT-60U AT research,
  - High β_p H-mode (~ITER Hybrid)
  - Reversed shear (~ITER SS)

  have been developed

Sakamoto (Thu, AM)



ITER operation scenarios

Scenario	Plasma current [MA]	β_N	$H_{H98(y,2)}$	f_{NI}	l_i	Burn duration [s]	
Inductive (Scenario 2)	15	1.8	1.0	0.15	0.8	~400	Standard
Hybrid (Scenario 3)	~12	2-2.5	1-1.2	~0.50	0.9	≥1000	Advanced
Steady-state (Scenario 4)	~9	≥2.6	≥1.3	1.00	0.6	3000[a]	

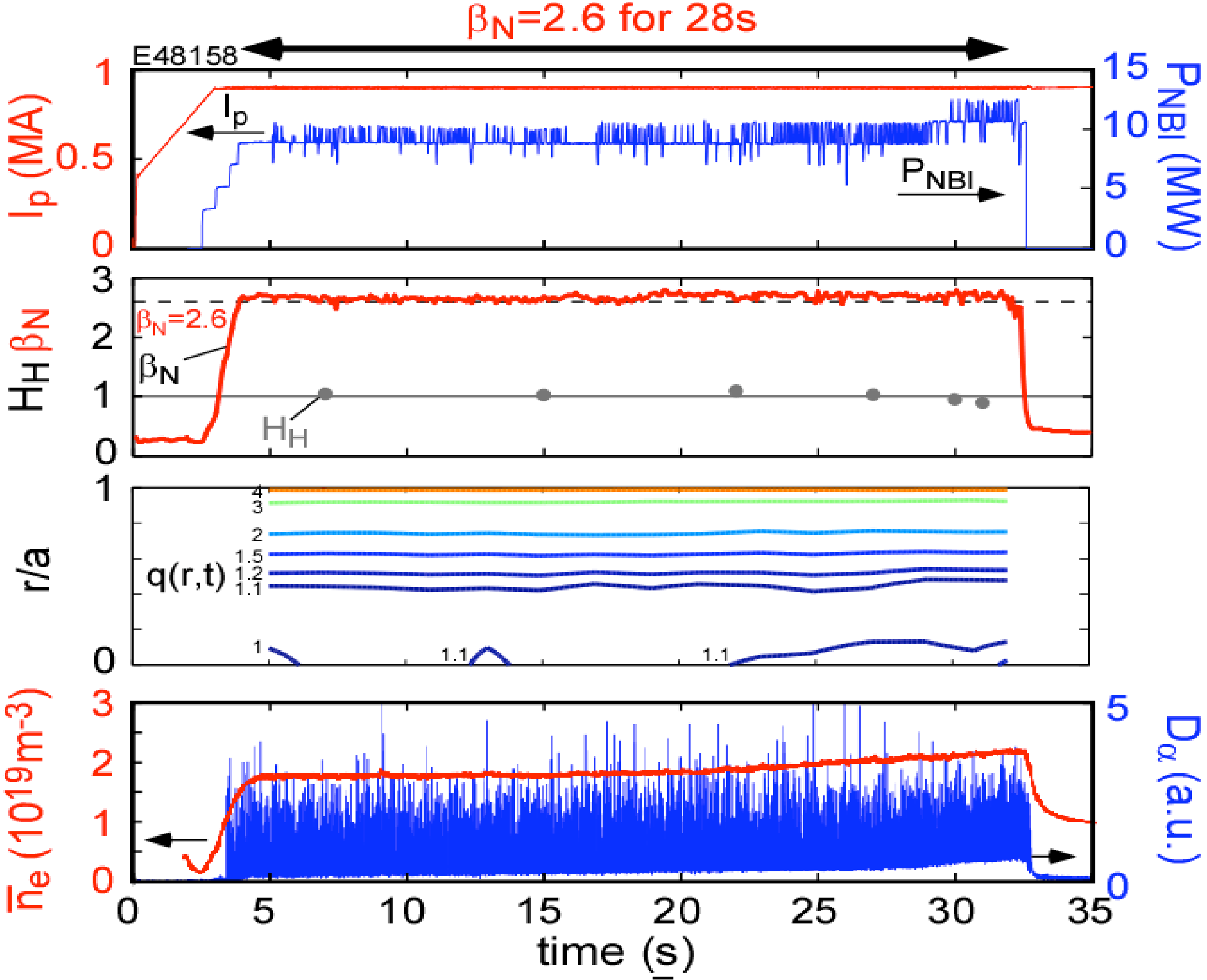
[a] 3000s limit is imposed by the cooling system

Progress in ITER Physics Basis, Chap.1

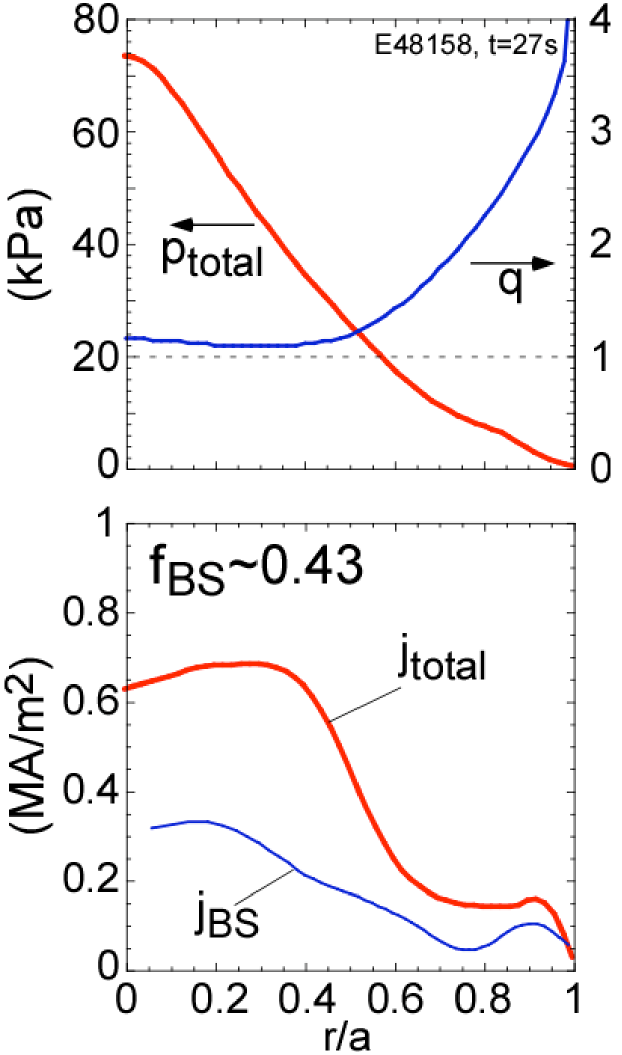
$\beta_N H_{H98(y,2)}$>2.6 was sustained for 25s (~14τ_R) in **high β_p H-mode** plasma

JT-60U

- **β_N=2.6, $H_{H98(y,2)}$=1.0-1.1, f_{BS}~0.4**: >~ ITER Hybrid performance
- **Avoidance of NTM** onset by p & q optimization:
  q=1.5, 2 surfaces far from steep ∇p

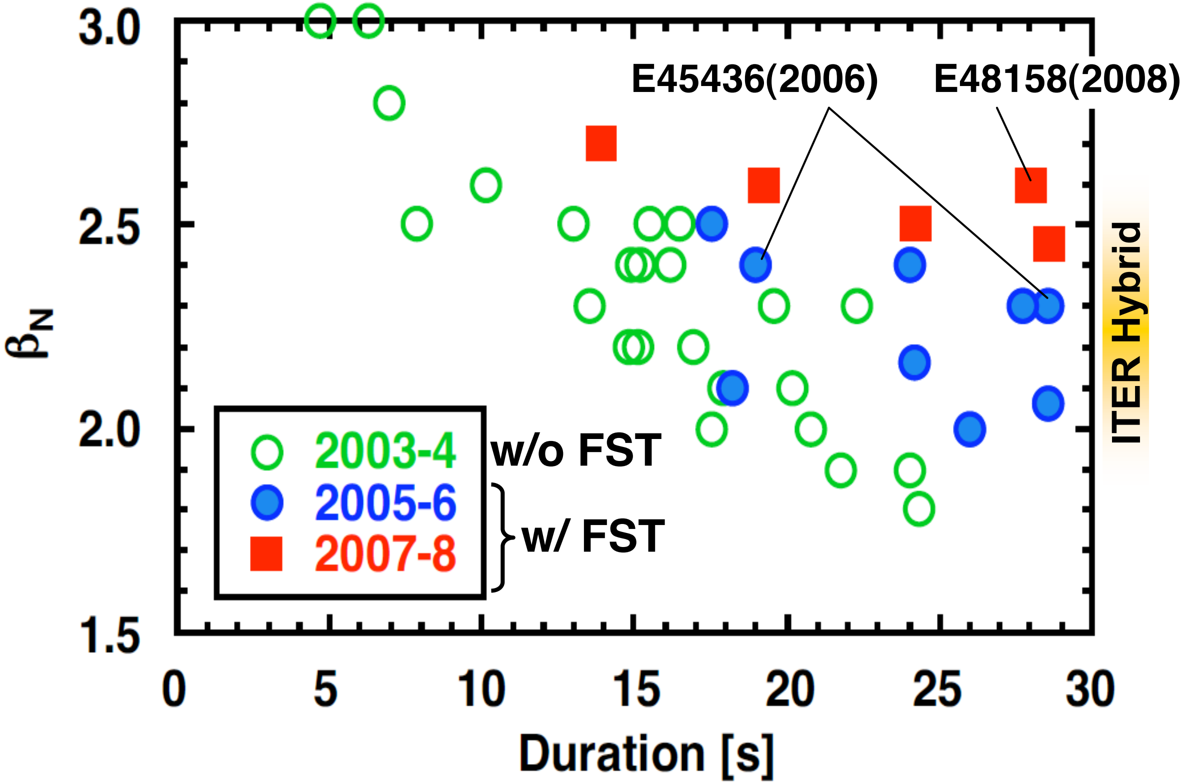


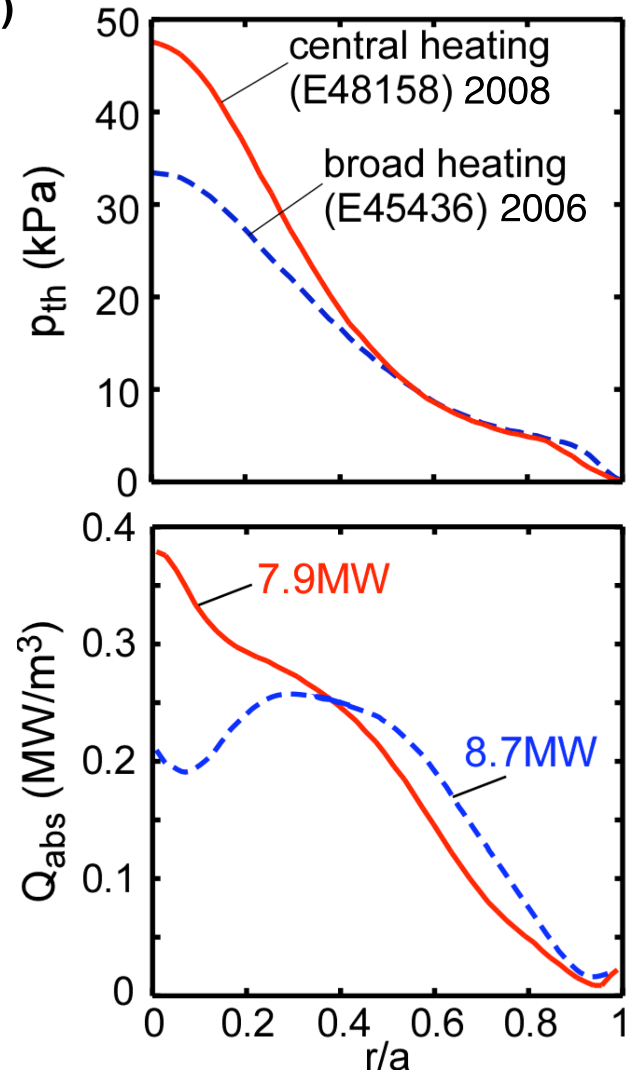
0.9MA/1.55T, q_{95}=3.2, H_H~1, $\bar{n}_e/n_{GW}$~0.49-0.55



Central heating is effective in keeping ITB

JT-60U

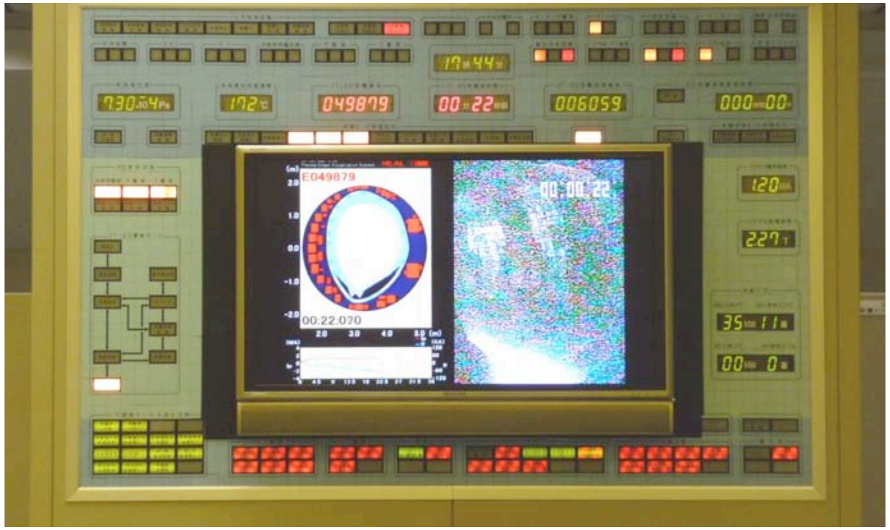




- **Fast ion loss has been reduced by installing ferritic steel tile (FST) (2005)**
- **Power supply of 3 PERP-NBs for central heating was modified for 30s injection (2007)**
- **Peaked pressure can be kept with smaller P_{net}**

Physics understanding in JT-60U AT regime

- *NTM suppression*
- *RWM suppression*



Last shot of JT-60U (2008/8/29)

NTM stabilization with ECCD in JT-60U

JT-60U

Neoclassical Tearing Modes (NTMs)

- appear in a high β plasma with positive shear

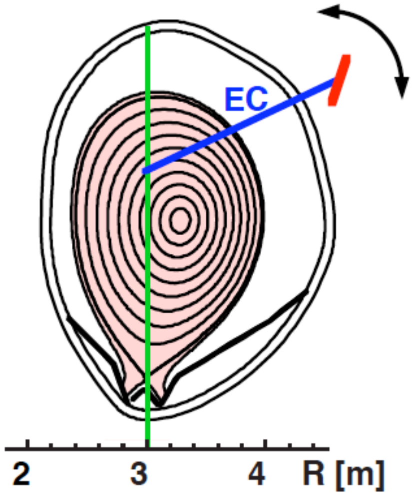
ITER Standard and Hybrid scenarios

- set achievable beta at $\beta_N < \beta_N^{ideal}$
- sometimes cause disruption

⇒ **NTM control is important:** m/n=3/2 and 2/1

NTM *avoidance* → long-pulse high-beta exp.

NTM *stabilization*: ECCD



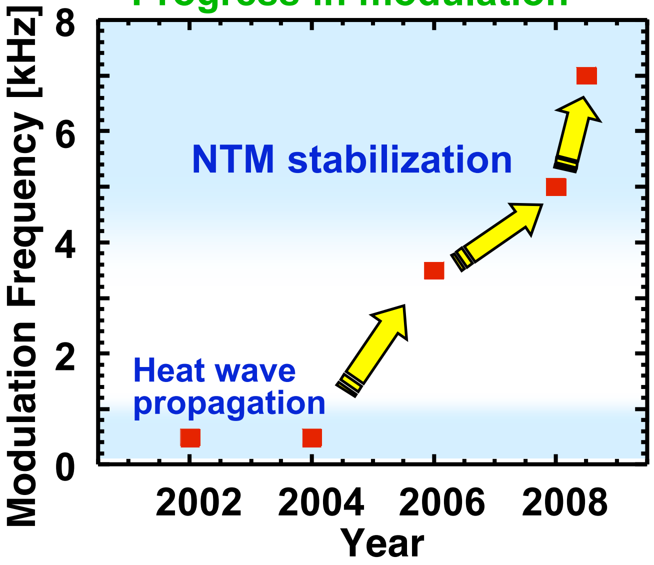
Previous results in JT-60U with ECCD

- Stabilization with O1 & X2 ECCD
- Stabilization with real-time mirror steering
- Preemptive stabilization
- Simulation with TOPICS-IB code

NTM research in 2007-8

- Stabilization with modulated ECCD

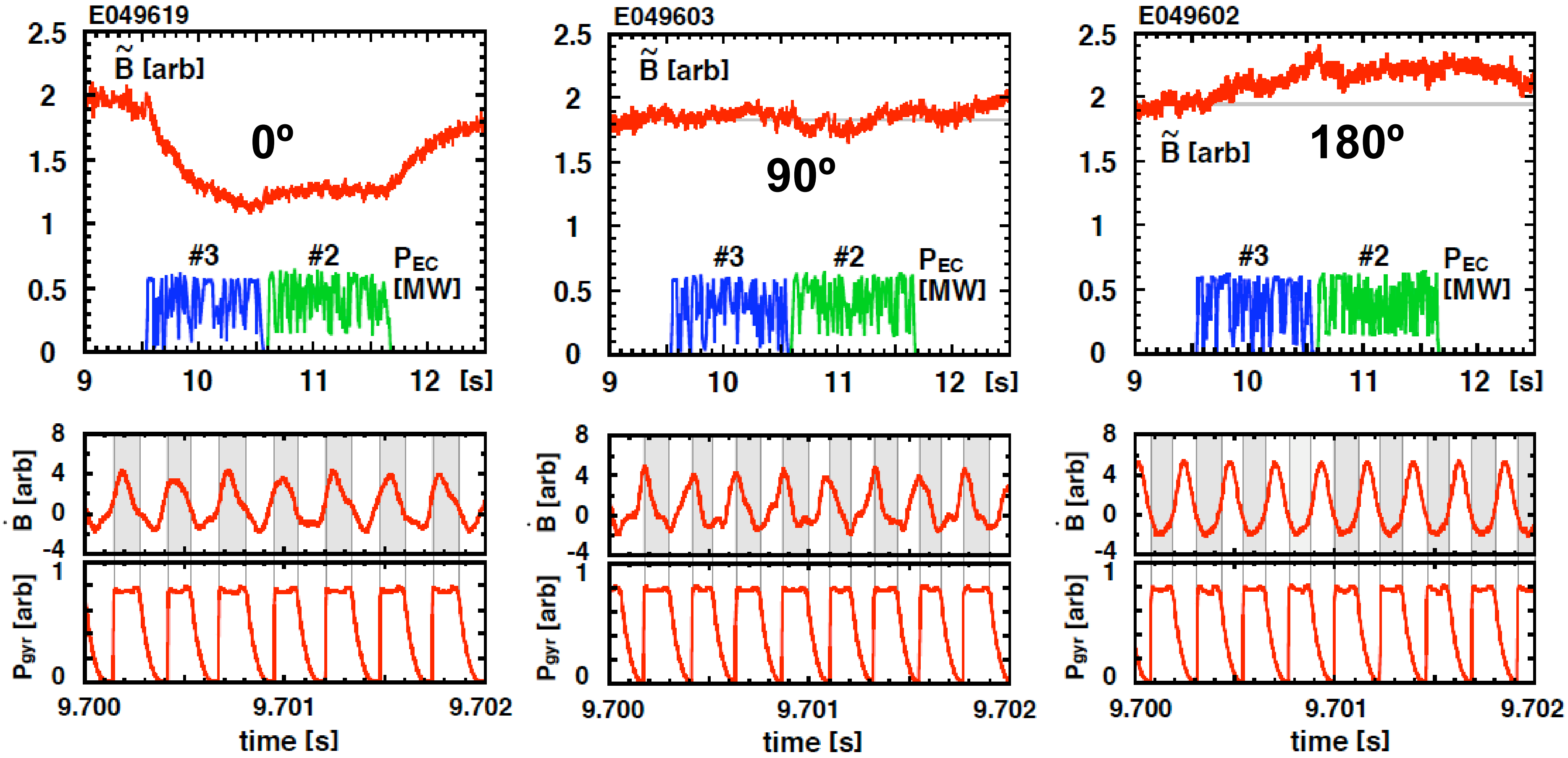
Progress in modulation



Stabilization effect is significantly affected by the phase difference between dB/dt and ECCD

JT-60U

- **Modulated ECCD**: **phasing** is required for O-point ECCD

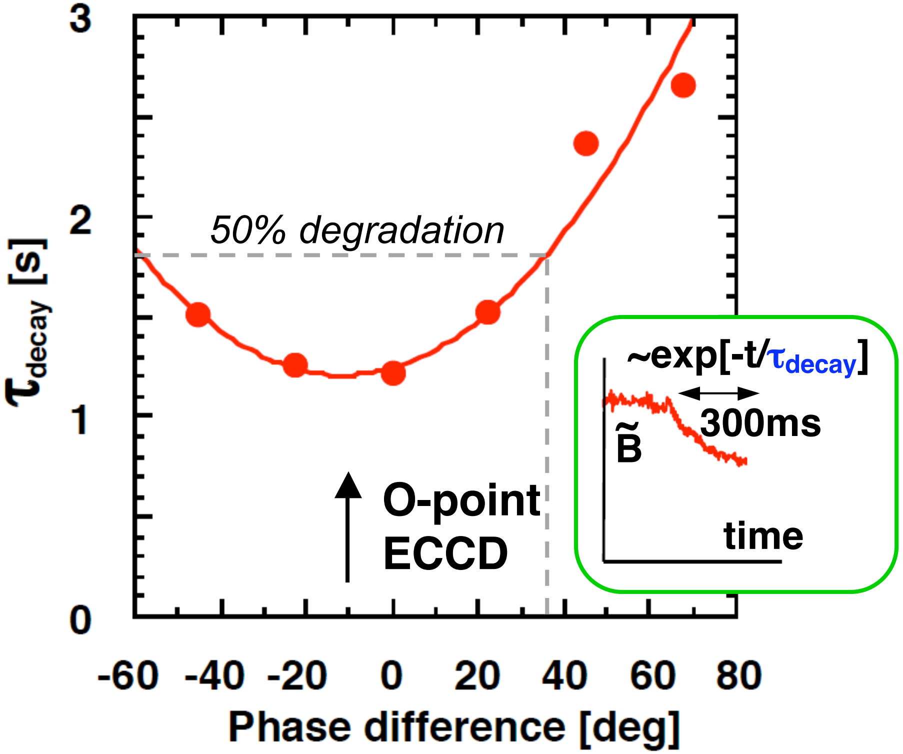


- **0º phase difference: stabilization effect**
- **90º phase difference: no clear effect**
- **180º phase difference: destabilization effect**

⇒ Phasing is important

Detailed phase scan showed that phase error should be smaller for effective stabilization

JT-60U



- τ_{decay}: minimum at ~ –10°
  ⇒ **O-point ECCD**
- τ_{decay}~4s for unmodulated ECCD
  ⇒ **modulated ECCD :**
  > x2 more effective

ECCD efficiency: η_{EC}

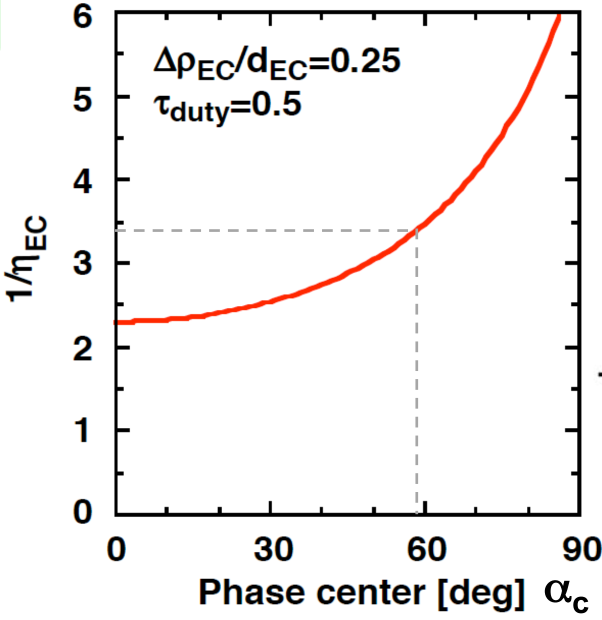
Hegna, PoP ’97
Perkins EPS ’97
Giruzzi, NF ’99

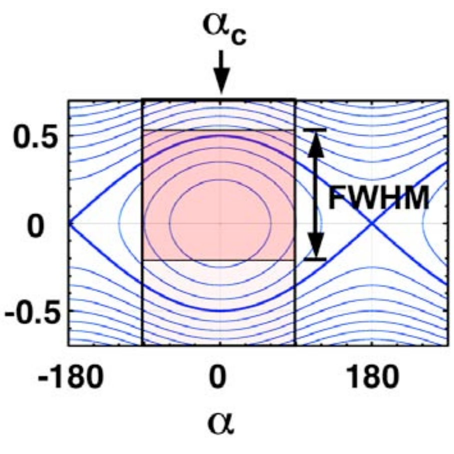
$$\eta_{EC}=\int_{-1}^{\infty}\bar{J}_{EC}(\Omega)\frac{R(\Omega)}{S(\Omega)}d\Omega \Big/ \int_{-1}^{\infty}\bar{J}_{EC}(\Omega)d\Omega$$

$$R(\Omega)=\oint\frac{\cos\alpha\, d\alpha}{\sqrt{\Omega+\cos\alpha}},\quad S(\Omega)=\oint\frac{d\alpha}{\sqrt{\Omega+\cos\alpha}}$$

Modified Rutherford equation

$dW/dt=f(W)-\eta_{EC}(W)\,g(W)$



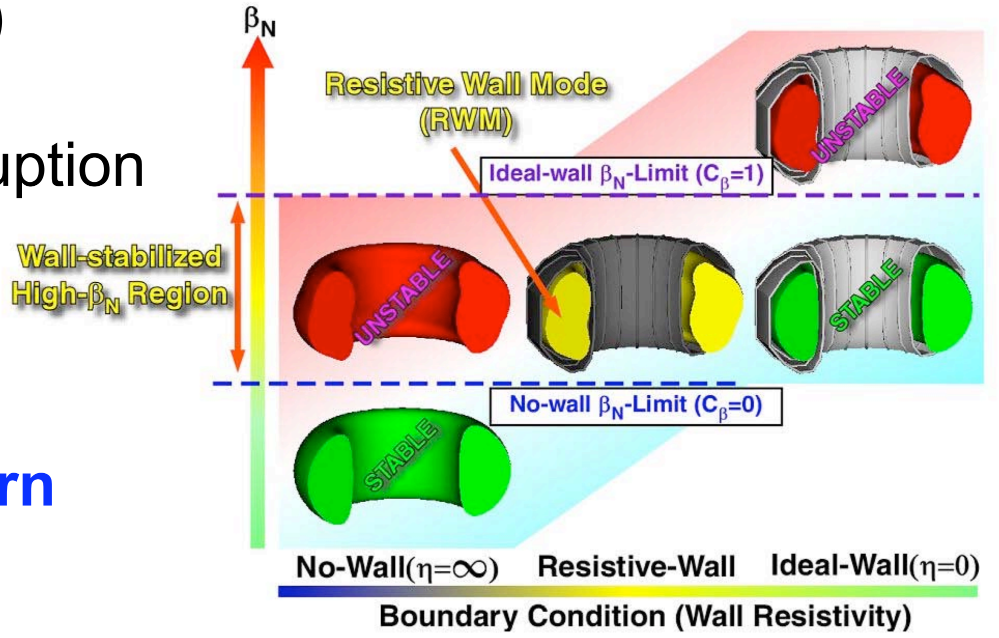


Similar to experiments

RWM study in JT-60U

Resistive Wall Modes (RWMs)

- appear at $\beta_N > \beta_N^{\text{no-wall}}$
- terminate the plasma by disruption



Rotation can stabilize RWM

⇒ **RMW control by V_t control**

JT-60U: Variety of NBI pattern

Previous RWM study

- Identification of minimum V_t for RWM stability

  ⇒ **V_t^{crit}~0.3% of V_A**

M. Takechi PRL (2007)

RWM research in 2007-8

- Detailed study on RWM stability (dV_t/dr, etc)
- Sustainment of $\beta_N > \beta_N^{\text{no-wall}}$ plasma

Two new instabilities have been observed just before RWM: ‘EWM’ and ‘RWM precursor’

JT-60U

- Discharge duration was limited by a variety of MHD instabilities

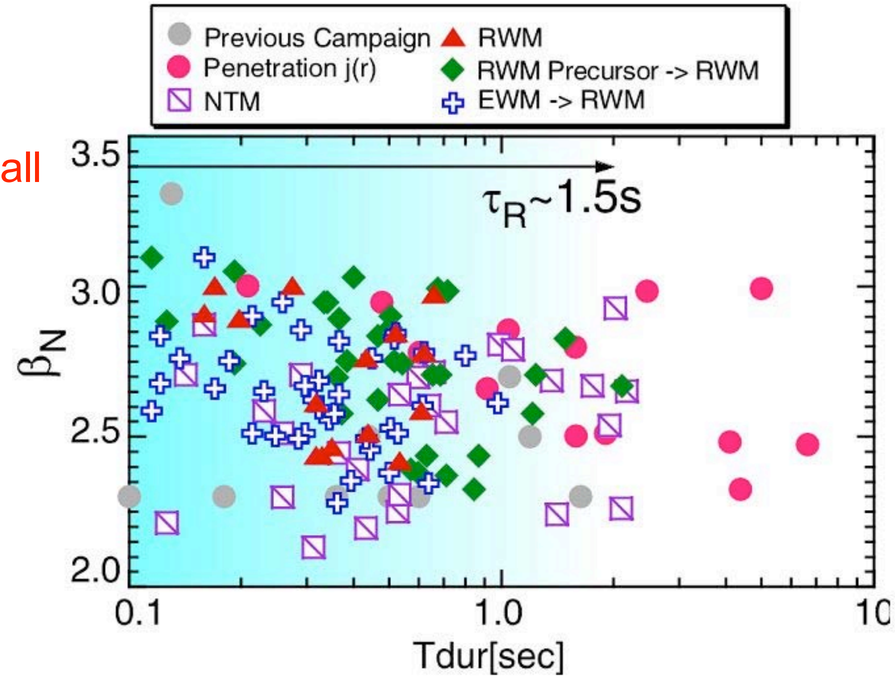
- **Two new instabilities** at $\beta_N > \beta_N^{\text{no-wall}}$

(1) Energetic particle driven Wall Mode (EWM)

directly induce RWM even at $V_t > V_t^{crit}$

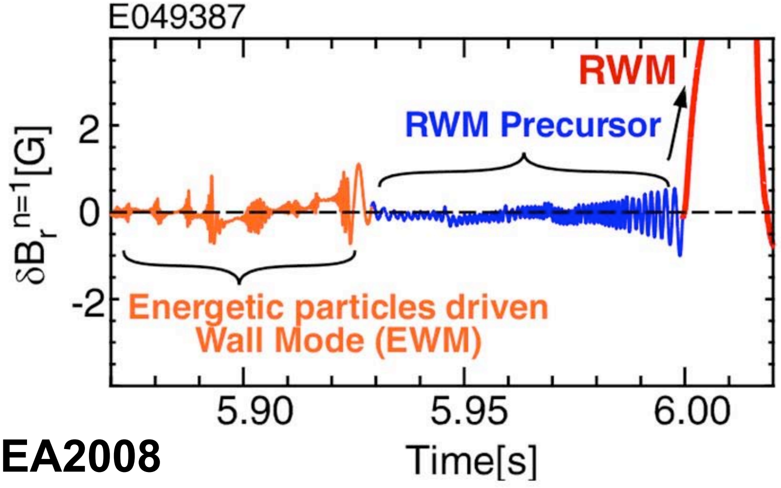
(2) RWM Precursor

strongly affects V_t profile at q=2, and finally induces RWM



Strategy for longer sustainment

- Sustain enough V_t & dV_t/dr to avoid RWM
- Reduce perpendicular NB to avoid EWM/RWM precursor



G. Matsunaga, IAEA2008

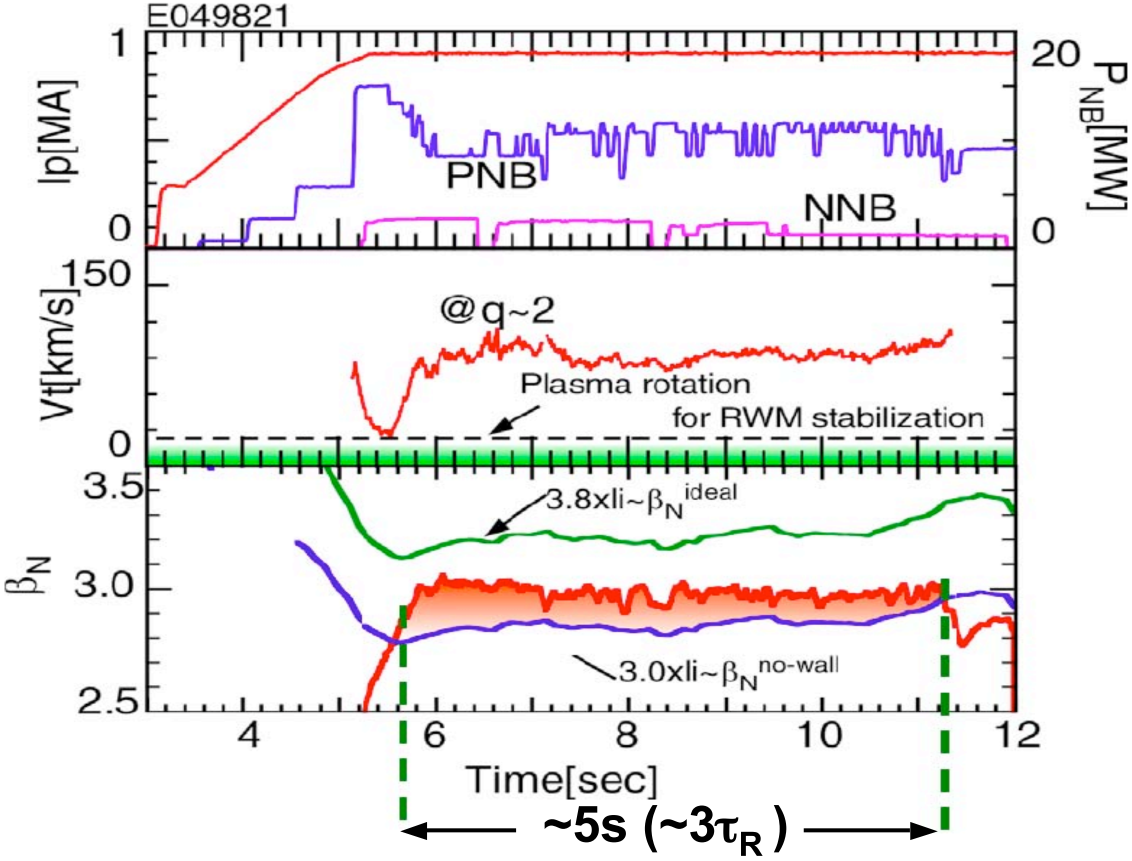
High β_N (> $\beta_N^{no\text{-}wall}$) was sustained for ~5s (~3τ_R)

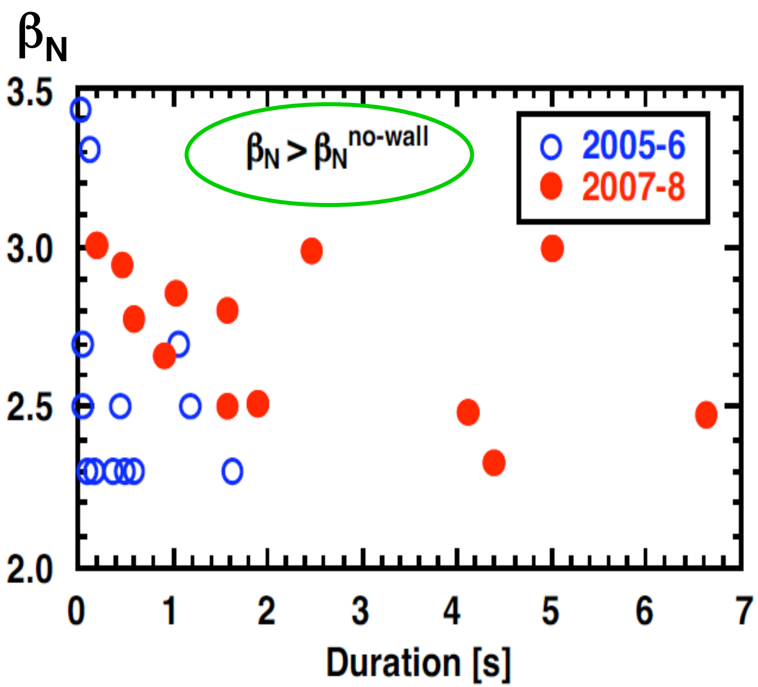
JT-60U

- β_N~3.0 (C_β~0.4) was sustained by keeping $V_t > V_t^{crit}$
- Sustained duration: ~5s (~3τ_R)

  ← limited by increase of $\beta_N^{no\text{-}wall}$ due to gradual j(r) penetration
- f_{NI}>80% and f_{BS}~50% (ACCOME code calculation)

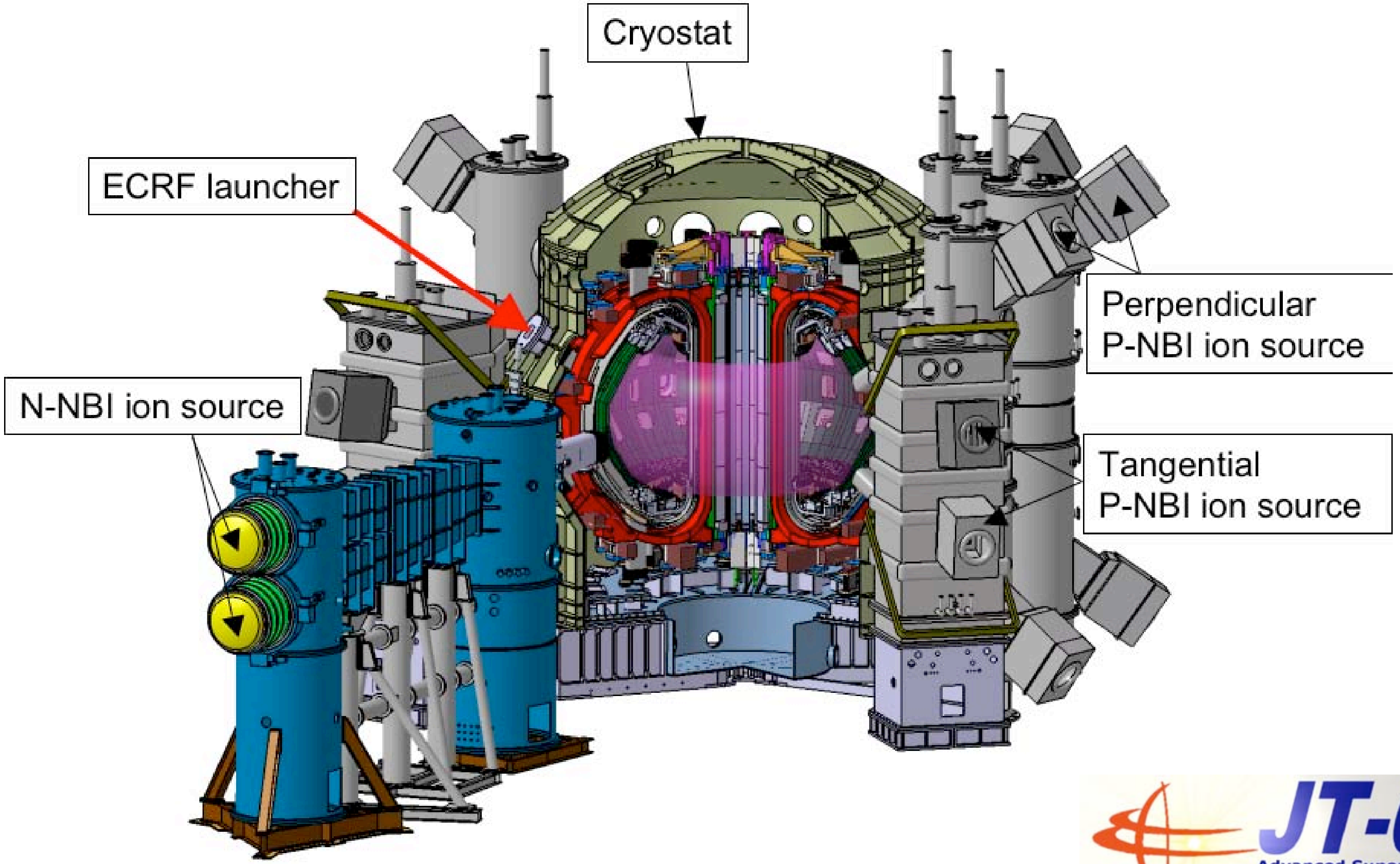
⇒ **Successful sustainment by RWM suppression**





High β_N regime above $\beta_N^{no\text{-}wall}$ has been extended

Physics assessment for JT-60SA



Cryostat

ECRF launcher

N-NBI ion source

Perpendicular
P-NBI ion source

Tangential
P-NBI ion source

JT-60SA
Advanced Superconducting Tokamak
BA-Satellite Tokamak Program

JT-60SA program

JT-60SA (JT-60 Super Advanced)

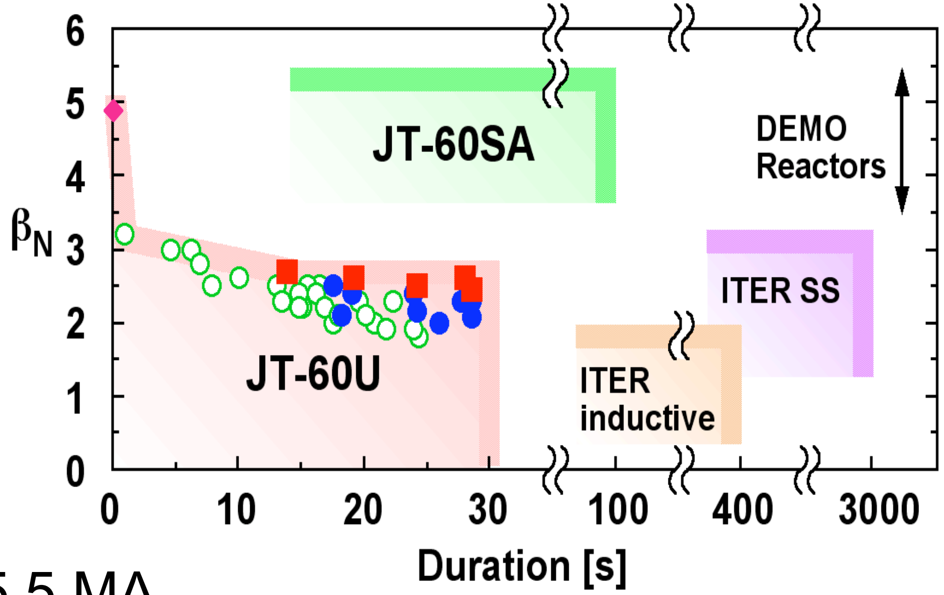
Combined program of

- ITER Satellite Tokamak Program of JA and EU
- Japanese National Program

Mission of JT-60SA

Early realization of fusion energy by

- supporting exploitation of ITER
- research toward DEMO



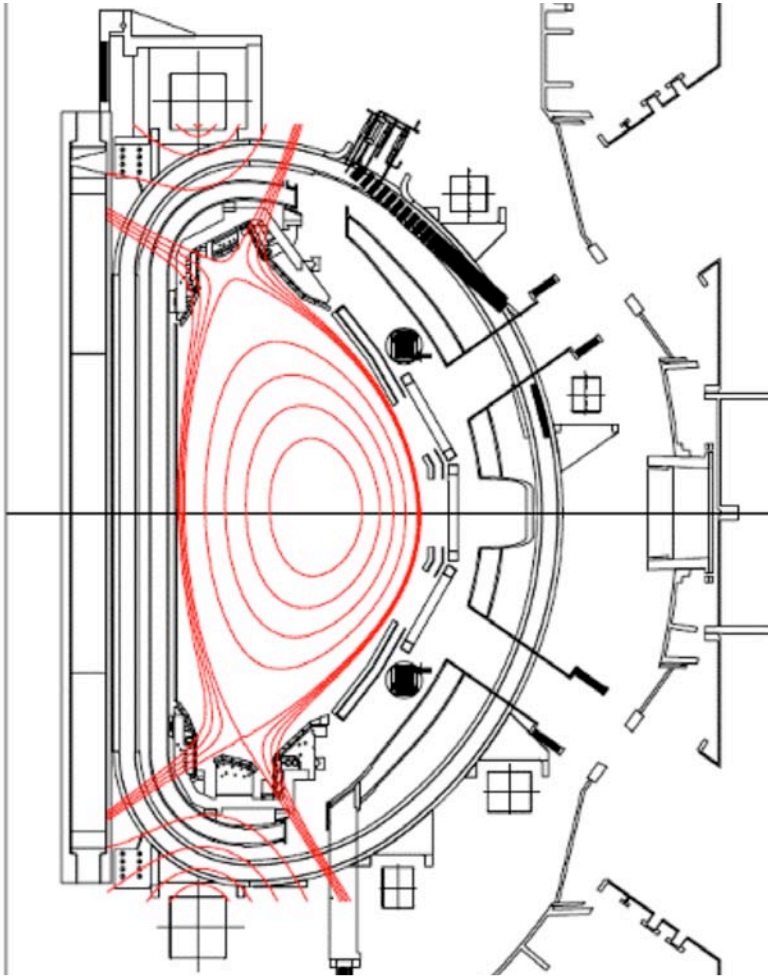
Target area of JT-60SA plasma

- Wide range of operational regime
  - Break-even class plasmas at I_p<~5.5 MA
  - High β_N full-CD plasmas for 100 s
- Wide range of plasma equilibrium
  - High shape parameter: S~6
  - Low aspect ratio: A~2.5

$$S=(I_p/aB)q_{95} \propto A^{-1}\{1+\kappa^2(1+2\delta^2)\}$$

- Better stability with higher A^{-1}, κ , δ
  ⇒ a measure of stability improvement
- β_t ($=S\beta_N/q_{95}$) increases with S

Main parameters in JT-60SA

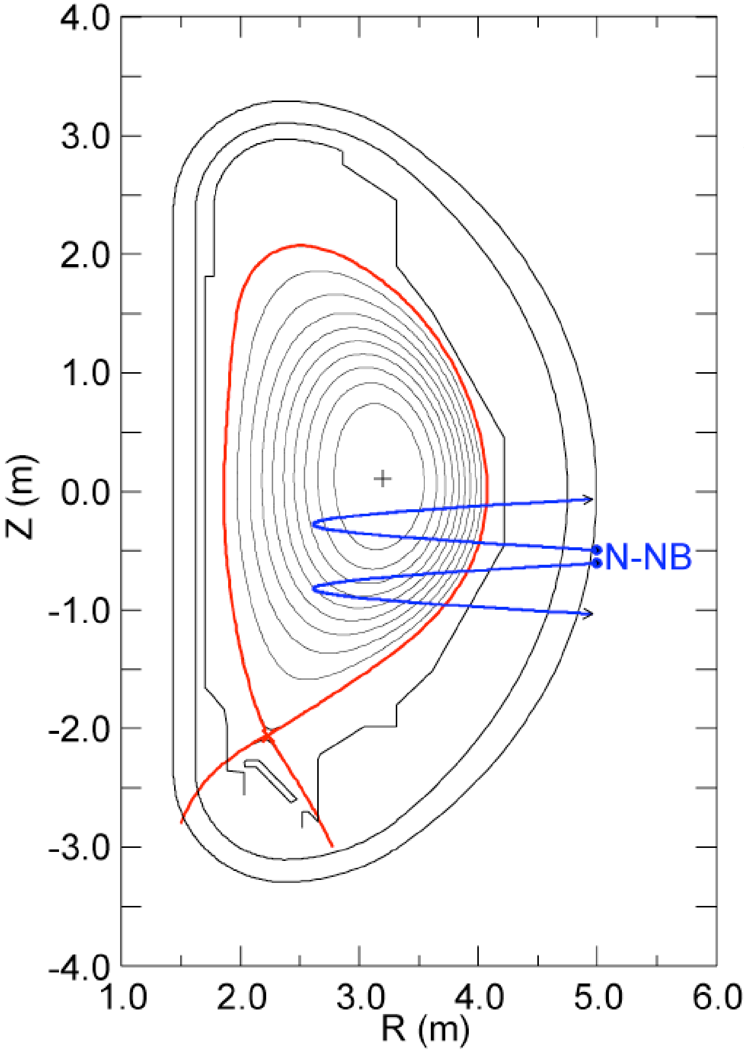


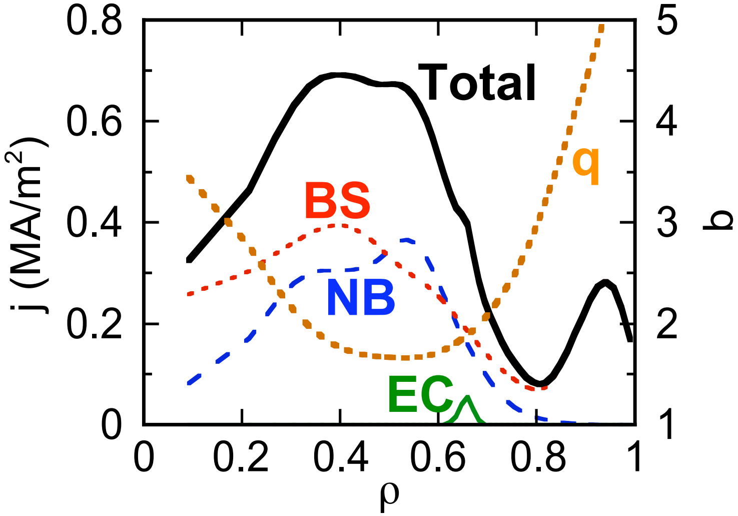
Active MHD stabilization tools

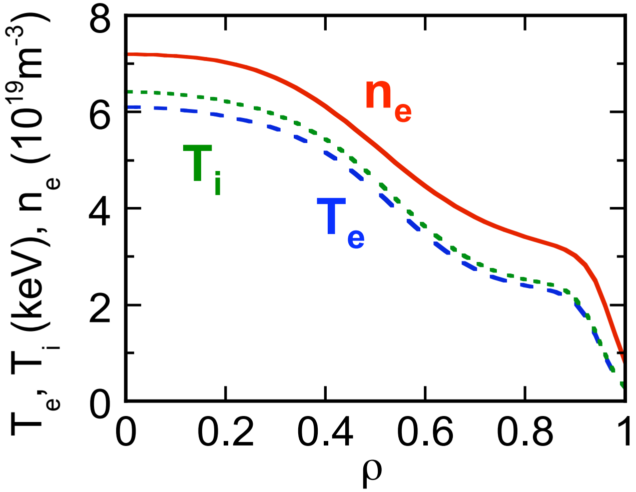
- 110GHz ECRF for NTM
- In-vessel coils for RWM

Nominal Parameter	
Major radius R [m]	2.97
Minor radius a [m]	1.18
Plasma current I_p [MA]	5.5
Aspect ratio A	2.5
Elongation κ_x	1.93
Triangularity δ_x	0.57
Safety factor q_{95}	~3
Toroidal Field B_t [T]	2.25
Plasma Volume [m^3]	~140
Greenwald density [$10^{20}m^{-3}$]	1.24
Shape Parameter S	6.1
Flattop flux @li=0.85 [Wb]	~8
TF Ripple at R+a	0.85%

Profiles in full consistent calculations of CD for steady-state scenarios







Example of Full-CD

I_p=2.3MA
B_t=1.76T
q_{95}=5.4
f_{GW}=0.85
f_{BS}=0.65
β_N=4.1
H_H=1.3
I_{BS}=1.49MA
I_{NB}=0.821MA
I_{EC}=0.015MA
P_{PNB}=20MW
P_{NNB}=10MW
P_{EC}=1.5MW

Summary

JT-60U advanced tokamak research

- **Long pulse high β_p H-mode**
  - High integrated performance plasma with β_N=2.6, $H_{H98(y,2)}$~1.0, f_{BS}=0.4 was sustained for 25s (~14τ_R) by NTM avoidance
- **NTM control**
  - Importance of phasing was demonstrated
  - Modulated ECCD is >x2 superior to unmodulated ECCD
- **RWM control**
  - 2 new instabilities at $\beta_N>\beta_N^{\text{no-wall}}$: EWM & RWM precursor
  - $\beta_N>\beta_N^{\text{no-wall}}$ was sustained for 5s (~3τ_R) by RWM suppression

JT-60SA advanced tokamak research

- **Design activity & physics assessment**
  - Wide range of operational regime and plasma equilibrium
  - Full CD capability confirmed by simulation